

Sediment Acoustics: LF Sound Speed, HF Scattering and Bubble Effects

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LONG-TERM GOALS

Physically sound models of acoustic interaction with the ocean floor including penetration, reflection and scattering in support of MCM and ASW needs.

OBJECTIVES

The objectives are to fill important gaps in our knowledge and understanding of ocean sediment acoustics, including (1) a new model to account for the recently measured low-frequency sound speed anomaly, (2) new scattering mechanisms to augment current Navy models of high-frequency bottom scattering, and (3) the study of time dependent propagation and scattering effects due to shallow water gas bubbles in the sediment.

APPROACH

New propagation model development: Previous accomplishments in sediment acoustics include (a) the detection of sub-critical angle penetration (Chotiros 1989, 1995a), (b) the realization that the effective density is less than the physical density (Chotiros 1995b and Williams 2001), (c) the composite medium extension of the Biot model (Chotiros 2002) which gave a better understanding of the boundary between frame and fluid, and (d) the relaxation mechanisms, also known as squirt flow, at the grain-grain contacts (Chotiros, Isakson 2004). There is a recently discovered anomaly that needs to be addressed: the low-frequency sound speed anomaly. Measurements at SAX04 (Hines, Osler, Scrutton, and Lyons, 2005), SAX99 (Williams et al. 2002) and a previous set of measurements by Turgut (Turgut, Yamamoto 1990) show sound speeds below 2 kHz that are significantly lower than the lower-bound predicted by the Wood equation. One possible cause is the presence of minute gas bubbles in the sediment, which current instrumentation is unable to resolve. Another, and more likely cause, may lie within the dynamics of the skeletal structure.

New bottom scattering model development: Initial measurements in 1960s (McKinney and Anderson 1964) and model studies, indicated that backscattering strength increased with frequency, and this was partially responsible for the frequency selection of the AN/SQQ-32 sonar. But later measurements did not uphold this trend. Measurements in the 1980s resulted in the APL-UW HFEVA bottom backscattering model. While this model was well-tuned to the 1980s data, it fit neither the earlier data nor the later data. These observations show that no one measurement, or program of measurements, has been able to capture the diversity of the seabed. A database of all the published measurements is

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needed to fully comprehend the scope of the problem. As an example of the utility of such a database, data accumulated prior to 1996 was used by the Sonar Optimization Working Group (SOWG) to make informed decisions regarding the appropriate application of current Navy models (Keenan, 2002). For basic research, statistical analysis of the database is expected to reveal hitherto undiscovered scattering mechanisms, and lead to new model development.

Time-dependent effects due to shallow water gas bubbles: Analysis of the HF backscattering database suggests that gas bubbles may be an important scattering mechanism. Previous modeling efforts (Boyle and Chotiros 1995) indicate that very small amounts of gas, less than 100 parts-per-million, may be responsible. New research suggests that shallow water gas bubbles are not a rare occurrence. A recent laboratory experiment, simulating conditions at the SAX99 experiment, suggests that the bubble population varies with sun light, causing daily variations in the backscattering strength of up to 20 dB (Holliday, Greenlaw, Rines, Thistle 2004). Current Navy models do not admit any time-dependent processes.

WORK COMPLETED

The completed work mainly falls under HF scattering and LF sound speed. The HF scattering work includes (1) participation in the Experiments for the Validation of Acoustic modeling techniques (EVA) sea trials, including the measurement of seafloor small scale topography, and (2) the modeling of the effect of seafloor roughness on the measured average magnitude of the reflection coefficient to provide a correction factor. The LF sound speed work includes (3) the derivation of the attenuation of sound propagation in granular media in the context of the new frame virtual mass concept. They are described in greater detail below.

(1) The EVA experiment provided a very high quality set of acoustic reflection and scattering data and a corresponding set of bottom roughness data for model validation and parameter inversion. To obtain a measure of the roughness, the data collection process consisted of the measurement of seafloor topography using an optical instrument (Chotiros, Isakson, Piper, and Zampolli 2007).

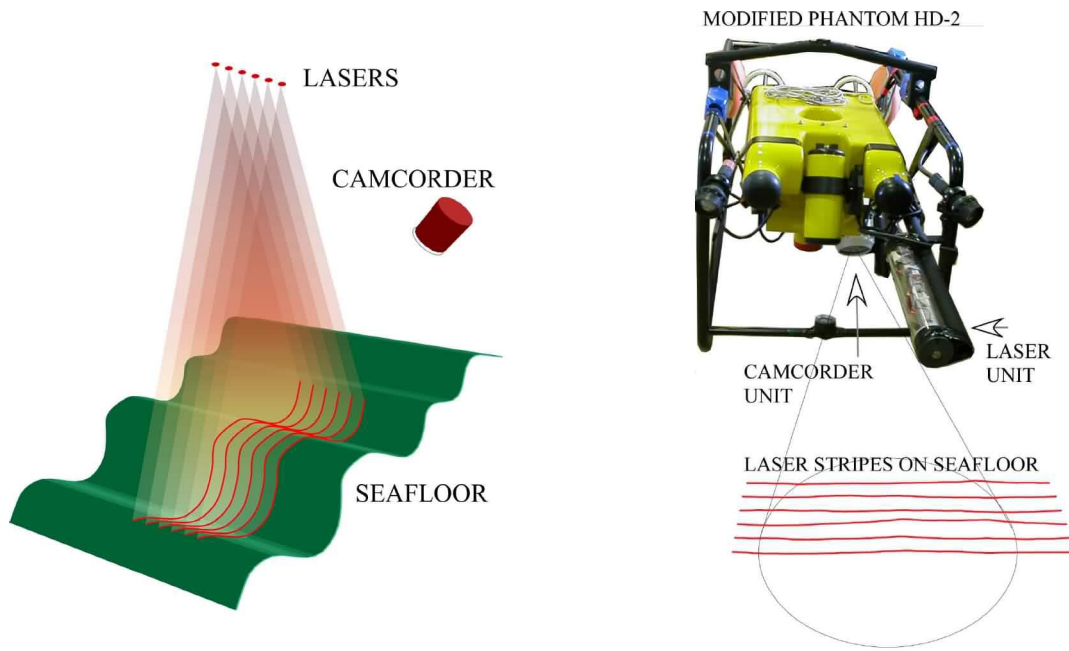


Fig.1 (a) Laser profiler concept and (b) Laser and camcorder units hosted on a modified Phantom HD-2 ROV. [(a) The seafloor is illuminated by a number of parallel laser stripes and the image is recorded at an oblique angle on a video camera. (b)The camcorder unit is mounted under a ROV and within its crash frame. The laser unit protrudes in front of the ROV.]

The basic concept consists of a number of lasers projecting parallel fan beams on the seafloor and a video camera to record the images, as illustrated in Fig. 1 (a). From the relative positions of the lasers and the camera, the 3-dimensional profile illuminated by each laser may be computed within a frame of reference centered on the camera. Then, using optical position tracking of the seafloor, the laser profiles were stacked to produce a representation of the swept surface. In this design, six lasers were used in order to maximize the data rate and provide continuous coverage of the seafloor. The redundancy was used in a self-consistency test to estimate accuracy. The goal was to achieve horizontal and vertical resolutions of 2 and 1 mm, respectively. The collection of laser profiles and the collection of seafloor images for navigation and stacking purposes were accomplished in one camcorder. The hardware was hosted on a modified Phantom HD-2 ROV originally made by Deep Ocean Engineering as illustrated in Fig. 1 (b).

(2) The effect of roughness on the reflection measurement was modeled analytically. The method of Yang, Fennemore and McDaniel 1992 would have been ideal, since it provides the fourth moment of pressure fluctuations, which can be directly compared with measured fluctuations in signal pressure amplitudes, but the scattering integral is difficult to solve and the numerical method provided by the authors is not applicable to the relatively low level of roughness that was measured in this experiment. The method chosen is that of Tolstoy and Clay 1987. It provides the second moment $\langle s^2 \rangle$ of pressure fluctuations due to reflection by a rough surface.

$$\langle s^2 \rangle = \frac{k^2 R^2 B^2 f^2(\theta) XY}{2\pi R_1^2 R_2^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} D_o' e^{2i(\alpha\xi + \beta\eta)} \left[e^{-4\gamma^2 \sigma^2 (1-\psi)} - e^{-4\gamma^2 \sigma^2} \right] d\xi d\eta$$

It requires the correlation function of the surface roughness ψ as input, which may be directly computed from the roughness wave number spectrum. The scattering geometry is shown in Fig. 2. The definition of the remaining terms may be found in the reference. Assuming a Rician distribution, the second moment may be converted into the fourth moment.

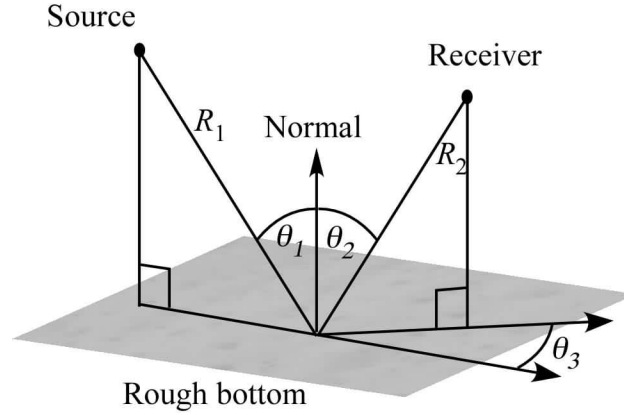


Fig. 2. Basic geometry. [A ray diagram from a source at distance R_1 and incidence angle θ_1 , above a rough bottom, to the receiver at a distance R_2 reflected angle θ_2 and bistatic angle θ_3]

(3) Further progress was made in the development of a new model for low frequency sound propagation in water-saturated granular ocean sediments. The modeling of the mechanical coupling between grains in a randomly packed unconsolidated granular medium was extended to include attenuation of sound waves. Attenuation is modeled as the slippage of the grain-grain contacts. The number of contacts at each grain is greater than the minimum necessary to determine its position and orientation. The redundancy leads to conflict between contacts, and it is only logical that the weaker contacts would give way in the form of plastic failure and slippage, as illustrated in Fig. 3.

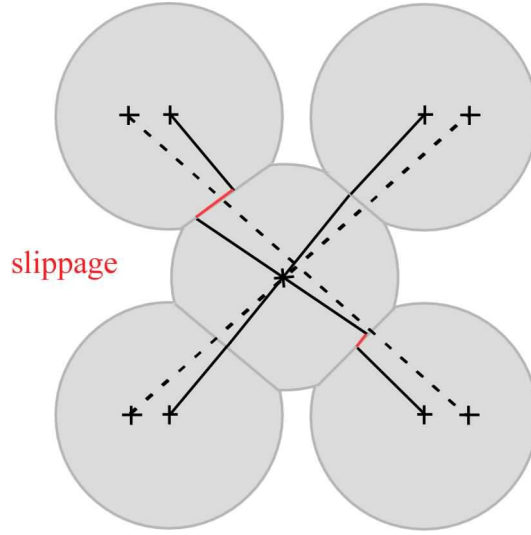


Fig. 3. Illustration of elastic and slipped contacts. [Diagram showing a spherical grain in the center, surrounded by 4 grains that have been pushed toward the center in two-dimensions. Random variation in contact stiffness tends to cause the weaker contacts to slip]

In addition to attenuation, the slippage will have consequences on the effective shear modulus of the medium, on the Poisson's ratio (Bachrach, Dvorkin and Nur 2000) and on the virtual mass terms, but it has negligible effect on the bulk modulus. The attenuation coefficient ζ , in Nepers/m, or the quality factor Q , may be defined in terms of the rate of energy change per unit volume L and the wave intensity I .

$$\alpha = -\frac{L}{2I}, \quad Q^{-1} = 2\alpha \frac{c_p}{\omega}$$

The rate of energy loss L , a negative quantity, may be defined in terms of the rate of energy loss per slipped contact L_c ,

$$L = N_v(N - N_b)L_c/2;$$

where N_v is the number of grains per unit volume, N is the average number of contacts at each grain, and N_b is the average number of elastic contacts (non-slip) at each grain. The most important term in the above equation is the average rate of energy loss at each slipped contact L_c . Starting with an assumption of viscous damping, the average rate of energy dissipation is proportional to the mean-square slip speed v_p^2 times the contact area, which is proportional to r^2 .

$$L_c = -C_e v_p^2 r^2$$

For simple fluid viscous damping, the parameter C_e would be a constant proportional to the viscosity divided by the average width of the gap at the contact between grains, but in general it should be regarded as an operator. Rather than simple viscous damping, current theories point toward a relaxation process, as put forward by Makse, Gland, Johnson, and Schwartz (2004), in which the slip

resistance initially has a high value, and drops to a very low value within a short relaxation time, which is expected to be associated with the mechanical response of the grain to an external force; it is likely to be proportional to the time it takes for a mechanical wave, such as a shear wave, to traverse a grain diameter. The operator C_e may be expressed in terms of a constant C_{eo} and a relaxation frequency ω_r ,

$$C_e = C_{eo}\omega/\omega_r ; \text{ for } \omega/\omega_r \ll 1.$$

RESULTS

The results are presented in the same order as the work completed:

(1) The laser profiler produced sections of seafloor topography. A small example is shown in Fig. 4(a). Measurements were made over linear tracks of over 5 m in length. The topographical data was processed to produce an average 2-dimensional wave-number spectrum as shown in Fig. 4(b). Significant values are contained within a radius of 50 cycles/m of the origin. The spectrum appears to be almost isotropic. Fourier transformation converts the spectrum into a correlation function that is used in the scattering integral.

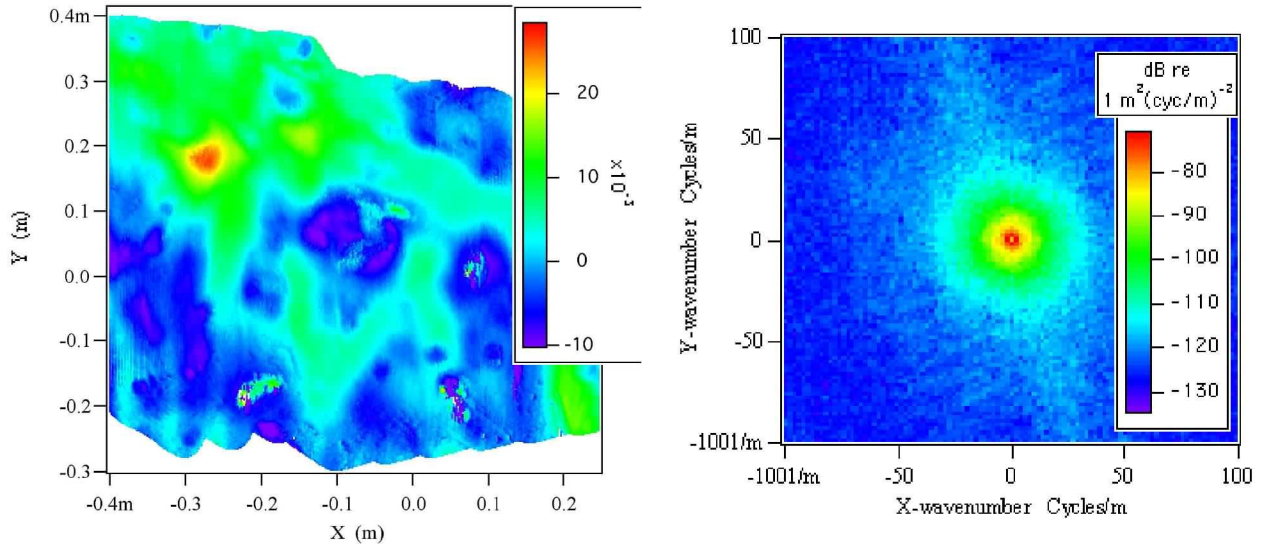


Fig. 4. (a) Example of measured seafloor topography and (b) average 2-dimensional wave-number power spectrum. [(a) The topography example shows height variations between -10 and +30 mm. (b) The spectrum is approximately isotropic with a peak in the center]

(2) Regarding the modeling of rough interface scattering, the RMS fluctuation in decibels of the reflected signal was estimated using the scattering integral approach. The theoretical estimates are compared with the measured fluctuation, as shown in Fig. 5, with fair agreement.

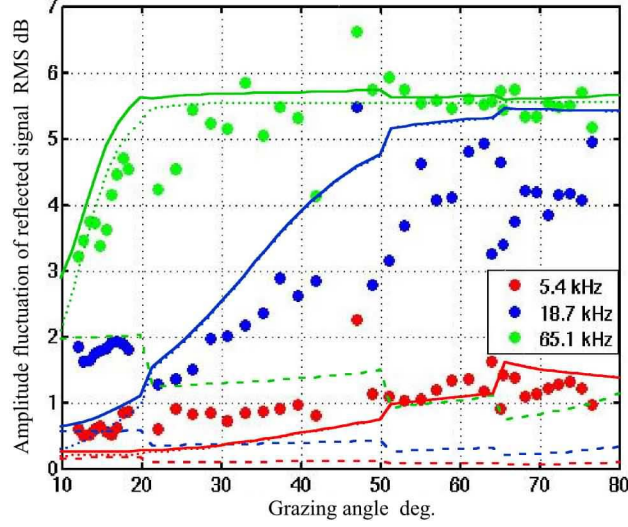


Fig. 5. Measured and estimated RMS reflected signal fluctuations as a function of angle.
[Data at three frequencies are compared to the corresponding theoretical estimates]

Encouraged by the agreement, the same approach was used to generate correction curves to convert the average reflection loss from a rough interface into the corresponding average values of an equivalent flat interface.

(3) Regarding the LF sound propagation in granular sediments, the following expression was obtained for the attenuation.

$$Q^{-1} = \frac{\sigma^2 C_{eo} (N - N_b) (9N + 2N_b R_{nt} (67R_{nt} - 9))}{40\pi (N + 2N_b R_{nt})^2 \sqrt{\rho_s G_s}}$$

where σ^2 is the scintillation index of the grain-grain contact stiffness, R_{nt} the ratio between the normal and tangential stiffness of an elastic contact, ρ_s and G_s are the density and shear modulus of the grain material. This expression has a number of desirable features. It indicates that attenuation is proportional to σ^2 and $(N - N_b)$. Both are expected to decrease with increasing pressure, which is qualitatively consistent with published measurements. It remains to apply this model to water saturated sediments. At the present time, it is still not possible to test the expression for the attenuation coefficient, because certain critical parameters are not yet measurable. However, the analysis also predicts an upper bound for the attenuation.

$$Q^{-1} < 2m_p/\pi$$

where m_p is the virtual mass for pressure waves, and its values are shown in Fig. 6 as a function of N and N_b . It is encouraging to note that all the known published attenuation measurements in granular media are below these upper bound curves.

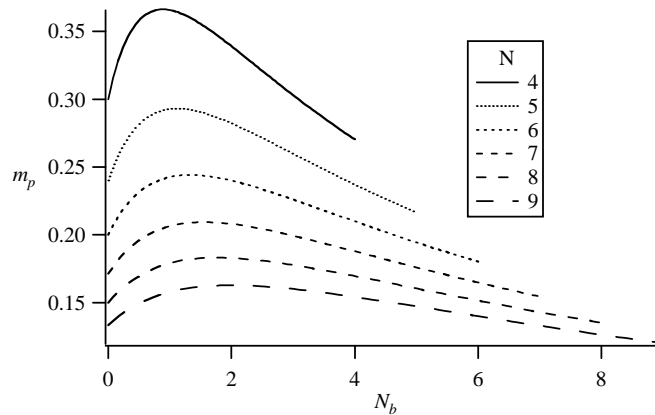


Fig. 6. Plot of the virtual mass term m_p , as a function of N and N_b . [The plot shows curves at values of $N=4,5,6,7,8$ and 9 , as a function of N_b . They peak at values of N_b between 0 and 2 .]

IMPACT/APPLICATIONS

The results will impact Navy underwater acoustic propagation models, particularly where reflection of sound from and penetration of sound into the ocean bottom are concerned. It will also impact the future structure of oceanographic databases maintained by Navy offices, including the Naval Oceanographic Office. Predictions of sediment sound speeds may need to be revised. In some cases, the effect on buried mine detection will be dramatic. In one particular instance (Chotiros, Mautner, Løvik, Kristensen, and Bergem 1997), it has been observed that the sediment sound speed changes from being faster than the speed of sound in water to being slower, as the frequency is reduced. In between the extremes, there is frequency range in which the sound speeds are almost perfectly matched, giving low transmission loss and improved buried mine detection performance. A summary of the findings has been presented to the Naval Oceanographic Office on 6 March 2007. Technical input was also provided to the Ocean Bottom Characterization Initiative (OBCI) planning meeting at the headquarters of the Commander of the Naval Meteorology and Oceanography Command (CNMOC), 10-11 April 2007.

RELATED PROJECTS

This project is closely related to most projects under the Underwater Acoustics: High Frequency Sediment Acoustics Thrust, and the on-going series of sediment acoustics experiments.

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PATENTS

1. An invention disclosure has been filed under the title: "Underwater laser profiler" with the University of Texas Office of Commercialization.